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DISCOVERY OF PARA-FORMALDEHYDE AND THE 2-MILLIMETER FORMALDEHYDE DISTRIBUTION IN THE ORION INFRARED NEBULA

P. THADDEUS
Goddard Institute for Space Studies, and Radiation Laboratory, Department of Physics, Columbia University

R. W. WILSON
Bell Telephone Laboratories

M. KUTNER
Department of Physics, Columbia University

AND

A. A. PENZIAS AND K. B. JEFFERTS
Bell Telephone Laboratories
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ABSTRACT

The 150.5-GHz line of ortho- and the 145.6-GHz line of para-H_2CO have been discovered in Ori A, and a detailed map of the previously detected 140.8-GHz ortho line has been obtained; H_2CO emission extends over a region whose dimensions are $\sim 3' \times 5'$, whose neutral-particle density is calculated to be $\sim 2 \times 10^5$ cm^{-3}, and whose total mass is $\sim 200\, M_\odot$; it is argued that the Kleinmann-Low infrared nebula is the central condensation of this cloud. The 140.8-GHz line has also now been found in Sgr A, W3(OH), and W51.

I. INTRODUCTION

In a recent Letter (Kutner *et al.* 1971, hereafter called Paper I) we reported detection of 140.8-GHz line emission from the Orion Nebula, and attributed it to the $2_{12} \rightarrow 1_{11}$ rotational transition of formaldehyde (H_2CO). We have now conclusively confirmed this identification by detecting at 150.5 and 145.6 GHz the two other $J = 2 \rightarrow 1$ formaldehyde transitions (see the energy-level diagram in Fig. 1), the latter belonging to the hitherto undetected para species of the molecule; an upper limit has also been obtained in Ori A for the $2_{11} \rightarrow 1_{10}$ transition of the isotopic species $H_2{}^{13}CO$, which falls at 146.6 GHz. A number of further observations have also been made of the 140-GHz line. It has now been found at locations where the 4.83-GHz line is observed, and in the Orion Nebula it has been mapped over a region of $\sim 3' \times 5'$ in extent.

Observations were made on 1971 February 12–14, as in Paper I with the 36-foot antenna of the National Radio Astronomy Observatory[1] equipped with a forty-channel filter-bank superheterodyne receiver. With our linear feed the measured half-power beamwidth of the antenna at 2 mm is 61″, and its beam efficiency is 0.61. The forty filters which determine the spectral resolution of the receiver are 2 MHz wide and are spaced 1 MHz apart. Frequency switching of the local oscillator was employed, and observations off the source, equal in duration to those on the source, were subtracted from the on-source observations to remove baseline irregularities.

[1] Operated by Associated Universities, Inc., under contract with the National Science Foundation.

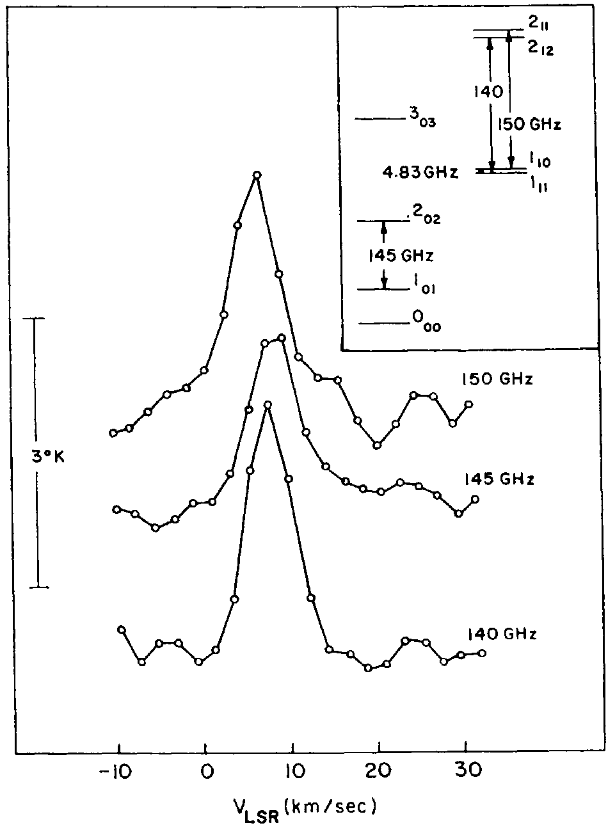

FIG. 1.—The $J = 2 \rightarrow 1$ lines of H_2CO in Ori A at location C. Insert shows the lower rotational energy levels of H_2CO, para levels on the left, ortho on the right.

II. OBSERVATIONAL RESULTS

a) *Orion Nebula*

Figure 1 shows the $J = 2 \rightarrow 1$ H_2CO lines at the location marked C in Figure 2, a point lying near the peak of the 140-GHz emission, within 1′ of the Trapezium, and in the direction of the infrared nebula of Kleinmann and Low (1967). Antenna temperatures and radial velocities of the three lines here and at the two nearby points A and B in Figure 2 are listed in Table 1, together with an upper limit which has been obtained for

TABLE 1

2-MILLIMETER FORMALDEHYDE LINES IN ORION A

Location on Map	α(1950)	δ(1950)	140.8 GHz* T_A (°K)	140.8 GHz* v_{LSR} (km s^{-1})	150.5 GHz† T_A (°K)	150.5 GHz† v_{LSR} (km s^{-1})	145.6 GHz‡ T_A (°K)	145.6 GHz‡ v_{LSR} (km s^{-1})	146.6 GHz§ T_A (°K)
A......	$5^h32^m46.9^s$	$-5°22'54''$	1.4	8.5	1.8	8.5	0.7	9.0	...
B......	5 32 46.9	−5 23 54	3.0	8.5	2.6	8.5	1.5	9.5	...
C......	5 32 46.9	−5 25 24	2.8	7.5	2.7	7.0	1.9	7.5	<0.2

Rest frequencies (Nerf 1971):
*140839.53. †150498.36. ‡145602.97. §146635.69 MHz (±0.03 MHz).

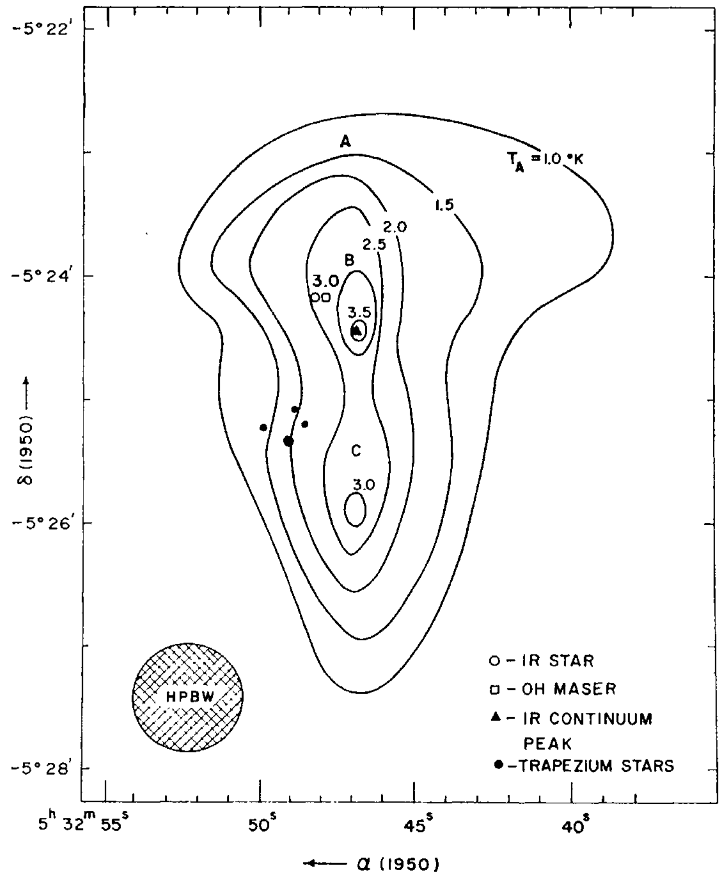

FIG. 2.—Map of 140-GHz H_2CO emission in Ori A, shown in relation to the infrared star of Becklin and Neugebauer (1967), the point source of OH emission (Raimond and Eliasson 1967), and the continuum peak of the infrared nebula. No correction in making this map has been made for the beamwidth of the antenna.

the intensity of the 146.6-GHz transition of $H_2{}^{13}CO$ at point C. Antenna temperatures T_A have been corrected for atmospheric attenuation, which was determined by antenna tipping, and was typically 8 percent at the zenith. Measurements of the T_A of a given line at separate locations, as in Figure 2, are relatively accurate to 5–10 percent, but because of calibration uncertainty caused by the reception of both sidebands the absolute scale of T_A is uncertain to $\sim$25 percent. To be converted to radiation temperature, $T_R = \lambda^2 I_\nu / 2k$, T_A in Ori A should be multiplied by 2.2, a factor which corrects for both beam efficiency and frequency smearing of the lines by the receiver filters.

Figure 2 is a map of the 140-GHz emission in the Orion Nebula, the result of a total of twenty-four observations, generally spaced a half-beamwidth apart in the center of the source, and a full beamwidth apart on its fringe. The velocity over the field is measured to be constant to within our velocity resolution of about 2 km s^{-1}.

b) Sgr A, W51, and W3(OH)

The observations of 140-GHz line emission from Sgr A, W51, and W3 are summarized in Table 2; the strongest line observed in each source is shown in Figure 3. In Sgr A the detected 0.8° line is located 2'.5 south and slightly to the east of the location where an

TABLE 2

140-GHz EMISSION IN OTHER SOURCES

Source*	α(1950)	δ(1950)	T_A(° K)	v_{LSR} (km s⁻¹)	Δv† (km s⁻¹)
W3(OH)........	2ʰ23ᵐ09ˢ	+61°39′00″	0.3	−45.5	9
	2 23 17	+61 38 00	0.5	−47.5	10
→	2 23 17	+61 39 00	0.8	−48.0	7
	2 23 17	+61 40 00	0.3	−50.5	10
	2 23 25	+61 38 00	0.3	−50.5	7
	2 23 25	+61 39 00	0.3	−50.0	12
Sgr A (NH_3 A)...	17 42 28	−29 01 30	0.8	+19.0	24
W51............	19 21 23	+14 24 30	0.8	+59.4	9
	19 21 27	+14 23 30	0.6	+55.4	12
→	19 21 27	+14 24 30	1.5	+53.4	11
	19 21 27	+14 25 30	0.8	+52.4	11
	19 21 31	+14 24 30	0.5	+52.0	...

* Arrows indicate location of lines shown in Fig. 3.
† Line width at half-intensity.

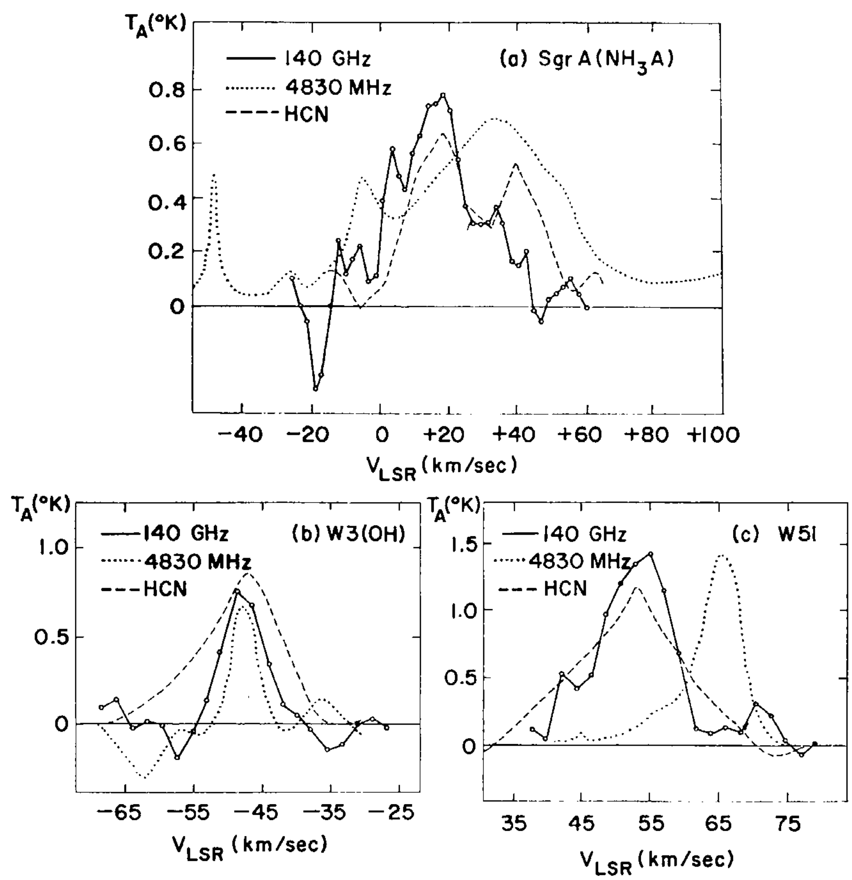

FIG. 3.—Profiles of 140-GHz emission in Sgr A, W3, and W51, at the locations indicated in Table 2. Published profiles of HCN 88-GHz emission (Snyder and Buhl 1971) and H_2CO 4.83-GHz absorption (Zuckerman *et al.* 1970), not drawn to the same intensity scale, and inverted in the case of 4.83-GHz, are shown for comparison.

upper limit of 0.7° was previously obtained, perhaps an indication that the Sgr A source is small; in W51 the line is found near the 2-cm continuum peak (Schraml and Mezger 1969). The following summarize the salient features of the observations:

1. The velocity and width of the 140-GHz emission so far always agree with that of the 88.6-GHz line of HCN (Snyder and Buhl 1971) and the 147-GHz line of CS (Penzias *et al.* 1971). Since comparable densities are required to excite these three transitions, this agreement is consistent with the idea that collisions are responsible for the line excitation.

2. In Sgr A and W51 distinct differences exist between the velocities of the 140-GHz and the 4.83-GHz formaldehyde lines.

3. In two out of three of the new sources, W51 and W3, the 140-GHz line, as in the Orion Nebula, appears to peak on, or very near, point sources of both OH (Raimond and Eliasson 1969) and H_2O emission (Knowles *et al.* 1969). And from preliminary mapping (Table 2) it appears that as in Ori A the 140-GHz source, though small, is distinctly extended.

III. DISCUSSION

It was concluded in Paper I that H_2CO emission in Ori A results from collisional impact, not ultraviolet or infrared photoexcitation, and that the total density required to excite the line is high—so high, in fact, that star formation must be taking place at a rapid rate. Since this conclusion may hold for other sources, and also for the recently discovered lines of HCN, CN, and CS (whose rates of rotational radiative transitions are comparable to that of H_2CO), it carries the important implication that molecular emission lines at millimeter wavelengths are generally signs of ultradense regions, and these lines for the first time provide spectroscopic tools for the study of the collapse of interstellar clouds and the formation of stars.

The new observations presented here strengthen this idea. The remarkable correlation of H_2CO emission with OH and H_2O maser point sources probably signifies that within the center of the observed clouds the density is so high that stars or protostars have already formed, and it is noteworthy that in Ori A at least one reaches the same conclusion by considering the relation of the molecular cloud to the infrared nebula. Consider first the density of the cloud, which can now be obtained to within relatively narrow limits from the observed absence of 2 mm emission by $H_2{}^{13}CO$.

a) Densities

We will assume that the $^{12}C/^{13}C$ abundance ratio in the Orion Nebula has the terrestrial value 89. Bortolot and Thaddeus (1969) and Smith and Stecher (1971) from optical spectroscopy have found comparable values of this ratio from, respectively, CH^+ and CO molecules in front of ζ Oph; and the terrestrial ratio is compatible with the results obtained by Zuckerman *et al.* (1969) in their 6-cm search for $H_2{}^{13}CO$ (except possibly in the region of the galactic center).

Consider now emission produced by an optically thin line whose excitation temperature is large with respect to that of the background radiation. The radiation temperature in the line center is

$$T_R = 2.2T_A = \frac{hc^2 AfN}{8\pi\nu\Delta\nu k}, \qquad (1)$$

where A is the rate of spontaneous radiative decay and f is the fractional population of the upper level of the transition, N is the column number density of molecules, and $\Delta\nu$ is the line width. We obtain an *upper* limit to the column density of normal ortho molecules by applying equation (1) to the undetected 2-mm line of $H_2{}^{13}CO$, setting $N = \frac{1}{89} N_{\text{ortho}}$, and assigning as a lower limit to f the value 4.4 percent obtained when all ortho levels are in equilibrium at 60° K, the cloud kinetic temperature adopted in Paper I. Similarly, we obtain a *lower* limit to N_{ortho}, valid even if the line is optically thick, by applying equation (1) to either the 140- or the 150-GHz transition of normal formaldehyde, and assigning as a reasonable upper limit to f the value $\frac{5}{16}$ obtained if only the $J = 1$ and 2 levels are populated, each in proportion to its statistical weight. The limits so obtained are

$$6 \times 10^{13} \leq N_{\text{ortho}} \leq 1.8 \times 10^{15} \text{ cm}^{-2} . \tag{2}$$

Thus a reasonable value to adopt for N_{ortho} in Ori A is

$$N_{\text{ortho}} \sim 3 \times 10^{14} \text{ cm}^{-2} . \tag{3}$$

Although in Paper I we considered both possibilities, let us now suppose that impact by neutral particles, not electrons, is responsible for the 2-mm H_2CO excitation. Cosmic rays are unlikely to produce the required ionization of several tens of electrons per cubic centimeter, and because of the dust and heavy obscuration probably associated with the molecules, it is hard to believe that such high ionization could be produced by starlight. Taking the neutral particles to be mainly H_2, we then find from White's (1971) theoretical investigation of the formation of interstellar H_2CO lines that if N_{ortho} is given by equation (3), a density of hydrogen molecules equal to

$$n_{H_2} \sim 2 \times 10^{5} \text{ cm}^{-3} \tag{4}$$

is required to produce a $\sim 7°$ K emission line at 140 or 150 GHz, a value consistent with the neutral-particle densities estimated in Paper I. If now as in Paper I we adopt 1×10^{18} cm for the thickness of the cloud, we next find

$$N_{H_2} \sim 2 \times 10^{23} \text{ cm}^{-2} , \tag{5}$$

and a H_2CO/H_2 ratio of

$$N_{H_2CO}/N_{H_2} \sim 2 \times 10^{-9} , \tag{6}$$

which is in quite good agreement with the results obtained from 4.83-GHz absorption in a number of sources (Zuckerman *et al.* 1970). The overall mass of the cloud derived from these figures is then

$$M \sim 200 M_{\odot} . \tag{7}$$

b) Infrared Nebula

It is evident from the foregoing density estimates that the molecular cloud in Ori A must be extremely opaque. The usual interstellar-extinction ratio, 1×10^{21} H_2 molecules per magnitude, implies by equation (5) a visual extinction of about 200 mag. This value is so large that even the infrared opacity of the cloud is appreciable: simple grain models and extrapolation of the optical data imply an opacity of 1–10 at a wavelength of 10 μ. This means, as does the coincidence of the 140-GHz emission peak with that of the infrared continuum (Fig. 2), that the infrared nebula discovered by Kleinmann and Low (1967) is probably the central condensation of the molecular cloud, an idea supported by the agreement that exists between our estimates of density and extinction and those derived by Kleinmann and Low and by Hartmann (1967) from analysis of the infrared data.

The equality of the peak brightness temperature of the saturated 116-GHz line of CO ($\sim 60°$) and the peak brightness temperature of the infrared nebula ($\sim 77°$ at 20 μ) is therefore unlikely to be accidental (at least, if the CO temperature as assumed is a fairly reliable measure of the gas kinetic temperature); it implies instead some mechanism that couples the kinetic energy of the gas to the infrared radiation, an effect which would readily explain the observed sharp dropoff in the CO temperature beyond the edge of the infrared nebula (Wilson, Jefferts, and Penzias 1970). One possibility is that the usual interstellar "cooling" transitions are working in reverse near the infrared nebula, absorbing energy from the radiation and transforming it via collisions to the gas kinetic energy in the molecular cloud. One would expect this mechanism to operate best if all or most of the cooling transitions are exposed to radiation, and the fact that Hoffmann, Frederick, and Emery (1971) and Harper and Low (1971) have recently found Ori A to be a strongly emitting source even at 100 μ would seem to favor this idea.

c) Ortho-Para Ratio

The intensities of the Ori A ortho lines relative to the para can depend on the way in which the molecules are excited, and on trapping of the 2-mm line radiation; the relative line strengths therefore may depend on T_{kin}, n_{H_2}, and $N_{\text{H}_2\text{CO}}$, as well as the ratio of ortho to para molecules. A preliminary analysis indicates that the data summarized in Table 1, which yield a mean intensity ratio $(T_{150} + T_{140})/2T_{145}$ of about 1.8, are consistent with the cloud parameters derived above and an ortho/para abundance ratio of 3:1.

d) Collisional Pumping

Averaged over the three locations listed in Table 1, the mean intensity ratio of the Ori A ortho lines is $T_{140}/T_{150} = 1.0 \pm 0.4$, the uncertainty resulting largely from the uncertainty in calibration. This ratio suggests that the collisional-pumping mechanism proposed by Townes and Cheung (1969) to explain anomalous 4.83-GHz absorption in dark nebulae does not operate in the molecular cloud in Ori A, since this scheme posits preferential excitation by neutral impact of the 2_{12} over the 2_{11} level, and hence emission is expected to be more intense at 140 than at 150 GHz. According to White (1971), collisional pumping, if it is to account for the anomalous effect, requires $T_{140}/T_{150} > 1.5$ under the conditions of temperature and density we have deduced for the molecular cloud. Given the observational uncertainties, this conclusion must be regarded as tentative; but it is noteworthy that it is also reached from a consideration of 4.83-GHz observations (Kutner and Thaddeus 1971 [accompanying Letter]).

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